

Compact polarimetry in a low frequency spaceborne context

My-Linh Truong-Loï, JPL/Caltech

Anthony Freeman, JPL/Caltech

Pascale Dubois-Fernandez, ONERA

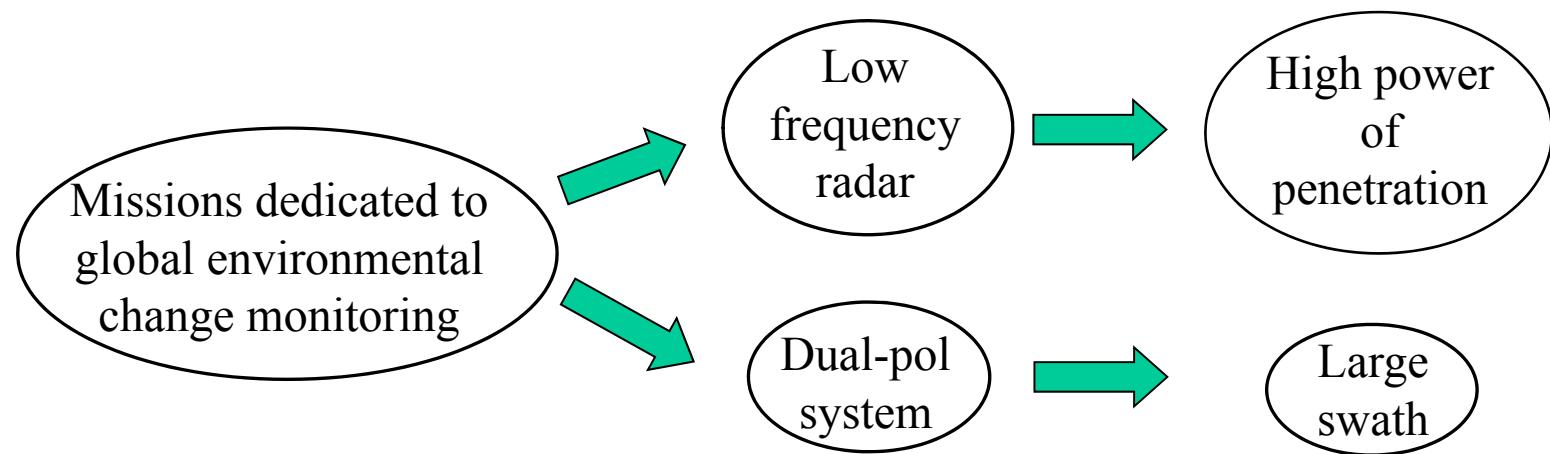
Eric Pottier, IETR, UMR CNRS 6164



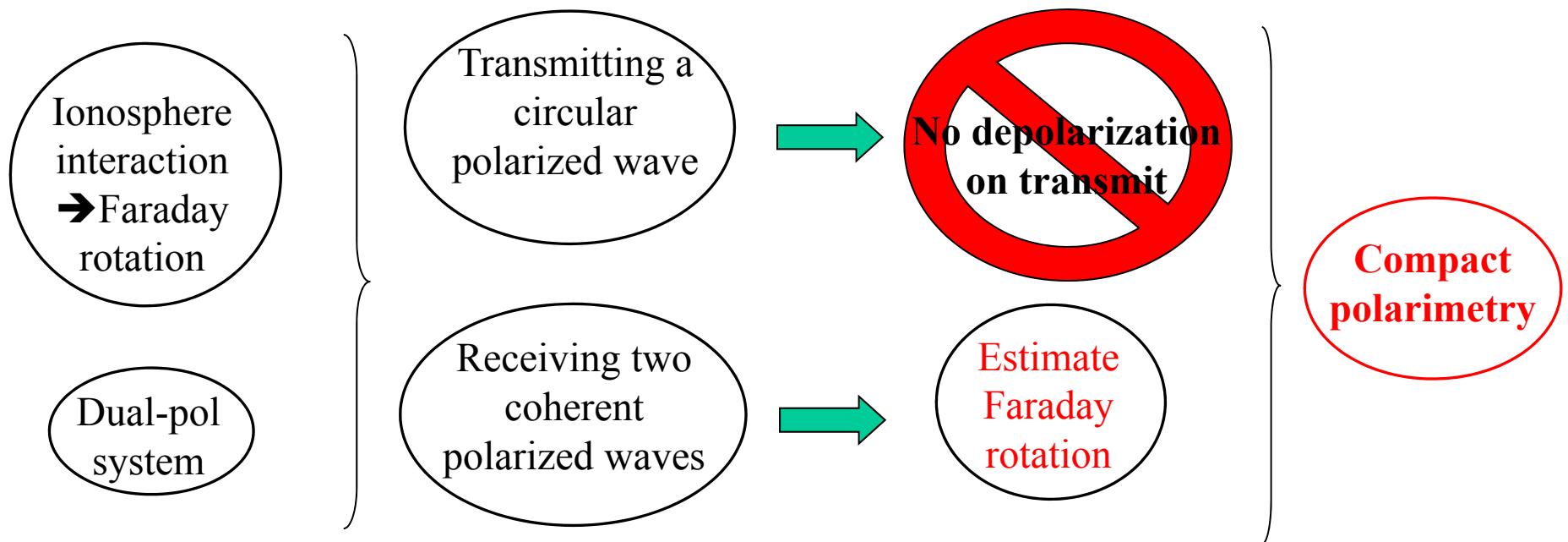
ASAR '11



Context – restrictions & reasons – 1/2



Context – restrictions & reasons – 2/2



Issues

- Compact polarimetry
 - 1 polarization on transmit
 - 2 polarizations on receive
- What is the best polarization on transmit?
- What are the best polarizations on receive?
- How do we analyze the data?
 - Calibration
 - Faraday Rotation
 - Geophysical parameter estimation
 - Compact PolSAR
 - Compact PollnSAR



ASAR '11



Overview

- Background
- Calibration
- Faraday rotation
- Classification
- Summary



ASAR '11



Overview

- Background
- Calibration
- Faraday rotation
- Classification
- Summary



ASAR '11



Background - Example with ALOS system

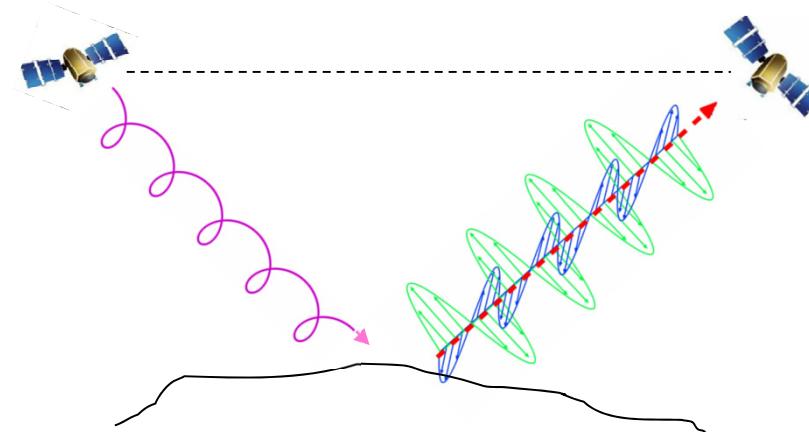
Mode	Swath	Resolution	Incidence angle
HH	70km	10m	8° ~ 60°
HH/HV or VV/VH (dual-pol)	70km	20m	8° ~ 60°
Full polar (quad-pol)	30km	30m	8° ~ 30°

- Single polarisation → large swath and larger incidence angle range
- Full polarisation → added characterisation
- Compact polarisation → full investigation of the dual-pol alternative

φ
p
r
e
s
e
r
v
i
n
g

Background - Compact Polarimetry 1/2

- $\pi/4$ mode: one transmission at 45° and two coherent polarizations in reception (linear H & V, circular right & left,...)



Background - Compact Polarimetry 2/2

- $\pi/4$ -mode potentials: reconstruction of the PolSAR information (1)
 - Iterative algorithm based on:
 - Reflection symmetry
 - Coherence between co-polarized channels
- $\pi/2$ -mode potentials: avoid Faraday rotation in transmission (2)
 - Transmit a circular polarized wave
 - Show results about the reconstruction of the PolSAR information from $\pi/2$ mode
- Hybrid polarity potentials: decomposition of natural targets (3)
 - m - δ method based on Stokes parameters

- (1) J-C. Souyris, P. Imbo, R. FjØrtoft, S. Mingot and J-S. Lee, *Compact Polarimetry Based on Symmetry Properties of Geophysical Media: The $\pi/4$ Mode*, IEEE Transactions on Geoscience and Remote Sensing, vol. 43, no. 3, March 2005.
- (2) P. C. Dubois-Fernandez, J-C. Souyris, S. Angelliaume et F. Garestier, *The Compact Polarimetry Alternative for Spaceborne SAR at Low Frequency*, IEEE Transactions on Geoscience and Remote Sensing, vol. 46, no. 10, October 2008.
- (3) R. K. Raney, *Hybrid-Polarity SAR Architecture*, IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, November 2007.



ASAR '11



Overview

- Background
- Calibration
- Faraday rotation
- Classification
- Summary



ASAR '11



Calibration – Full-pol system

- Full-pol system calibration : 7 unknowns $\delta_1, \delta_2, \delta_3, \delta_4, \Omega, f_1, f_2$

$$M = A(r, \theta) e^{j\varphi} D_R R_\Omega S R_\Omega D_T + N$$

$$M = A(r, \theta) e^{j\varphi} \begin{pmatrix} 1 & \delta_2 \\ \delta_1 & f_1 \end{pmatrix} \begin{pmatrix} \cos \Omega & \sin \Omega \\ -\sin \Omega & \cos \Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{VH} \\ S_{HV} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos \Omega & \sin \Omega \\ -\sin \Omega & \cos \Omega \end{pmatrix} \begin{pmatrix} 1 & \delta_3 \\ \delta_4 & f_2 \end{pmatrix} + N$$

- The S matrix can be recovered:

$$S = R_\Omega^{-1} D_R^{-1} M D_T^{-1} R_\Omega^{-1}$$

- Distortions can be retrieved with measures over known targets:
 - Trihedral, dihedral, transponder, natural targets, etc.

A. Freeman et T. Ainsworth, *Calibration of longer wavelength polarimetric SARs*, Proceedings of EUSAR 2008, Friedrishafen, Allemagne, June 2008.

S. Quegan, *A Unified Algorithm for Phase and Cross-Talk Calibration of Polarimetric Data – Theory and Observations*, IEEE Transactions on Geoscience and Remote Sensing, vol. 32, no. 1, pp. 89-99, January 1994.

J. J. van Zyl, *Calibration of Polarimetric Radar Images Using Only Image Parameters and Trihedral Corner Reflector Responses*, IEEE Transactions on Geoscience and Remote Sensing, vol. 28, no. 3, pp. 337-348, May 1990.



ASAR '11



Calibration – Compact-pol system

- Compact polarimetric system:

$$M = \frac{1}{\sqrt{2}} A(r, \theta) e^{j\varphi} D_R R_\Omega S R_\Omega D_T \begin{pmatrix} 1 \\ -j \end{pmatrix} + N$$

$$\tilde{R}_\Omega^{-1} \tilde{D}_R^{-1} M = \frac{1}{\sqrt{2}} S R_\Omega D_T \begin{pmatrix} 1 \\ -j \end{pmatrix}$$

Calibration – Compact-pol system

$$M \cong Ae^{j\varphi}e^{-j\Omega} \frac{1}{\sqrt{2}} \begin{pmatrix} S_{HH}(\cos \Omega - \delta_1 \sin \Omega) - jS_{VV}(\sin \Omega + \delta_1 \cos \Omega) \\ S_{HH}(\delta_2 \cos \Omega - f_1 \sin \Omega) - jS_{VV}(\delta_2 \sin \Omega + f_1 \cos \Omega) \end{pmatrix} + Ae^{j\varphi} \begin{pmatrix} S_{HV}(-j + \delta_1) \\ S_{HV}(-j\delta_2 + f_1) \end{pmatrix}$$

- Compact polarisation
 - 3 reference targets are necessary
 - Dihedral @ 0°
 - Dihedral @ 45°
 - Trihedral
- Full polarisation
 - More unknowns
 - But less targets are required
 - Natural targets can be used
 - Acquisition of both HV and VH



ASAR '11



Overview

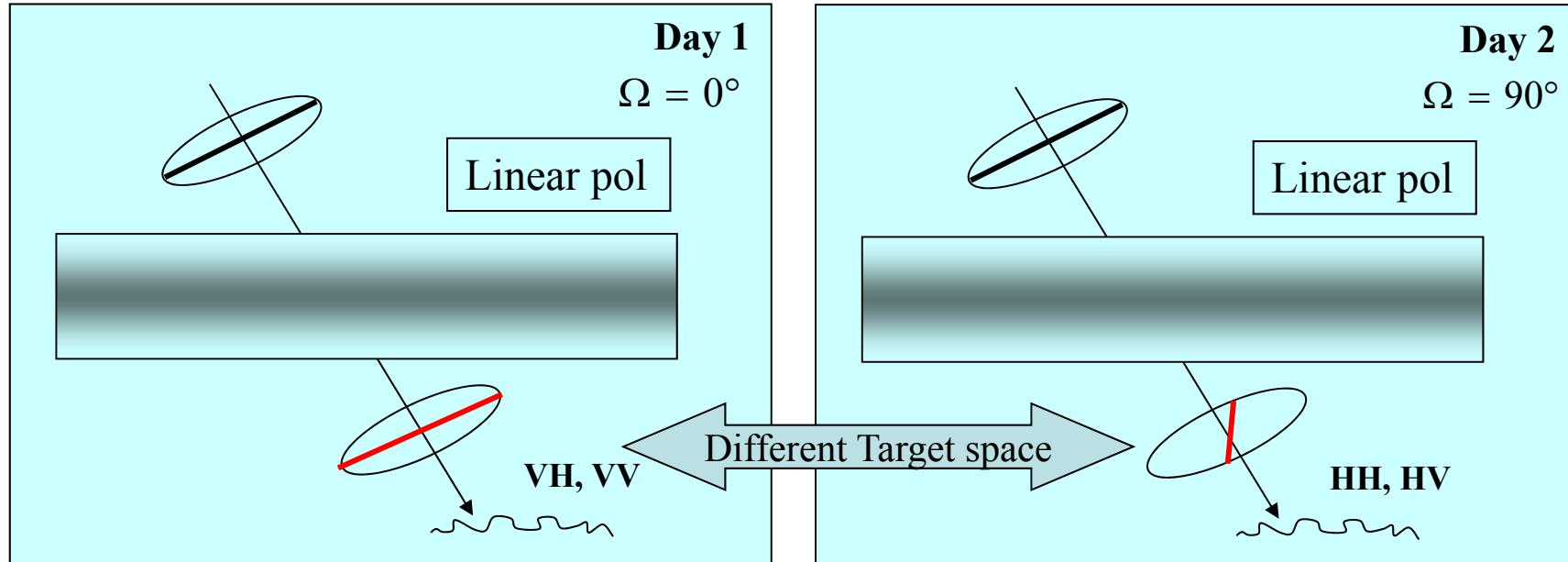
- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
- Classification
- Summary



ASAR '11



Faraday rotation – Illustration of ionosphere effect



Faraday rotation estimate using bare soil hypotheses

- Assuming a right circular wave in transmission:

$$\vec{J}_t = \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \overrightarrow{J}_{RC} = \frac{1}{\sqrt{2}} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} 1 \\ -j \end{pmatrix} = \frac{1}{\sqrt{2}} e^{-j\Omega} \overrightarrow{J}_{RC}$$

- Then the reception is:

$$\vec{k} = \begin{pmatrix} k_1 \\ k_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix} \begin{pmatrix} 1 \\ -j \end{pmatrix} = \frac{1}{\sqrt{2}} M \begin{pmatrix} 1 \\ -j \end{pmatrix}$$

$$\vec{k} = \begin{pmatrix} k_1 \\ k_2 \end{pmatrix} = \frac{1}{\sqrt{2}} e^{-j\Omega} \begin{pmatrix} S_{HH} \cos\Omega - j S_{VV} \sin\Omega - j e^{j\Omega} S_{HV} \\ -S_{HH} \sin\Omega - j S_{VV} \cos\Omega + e^{j\Omega} S_{VH} \end{pmatrix}$$

Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - ...
- Classification
- Summary

Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surface hypotheses
- Classification
- Summary



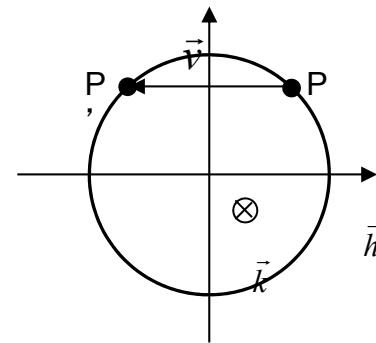
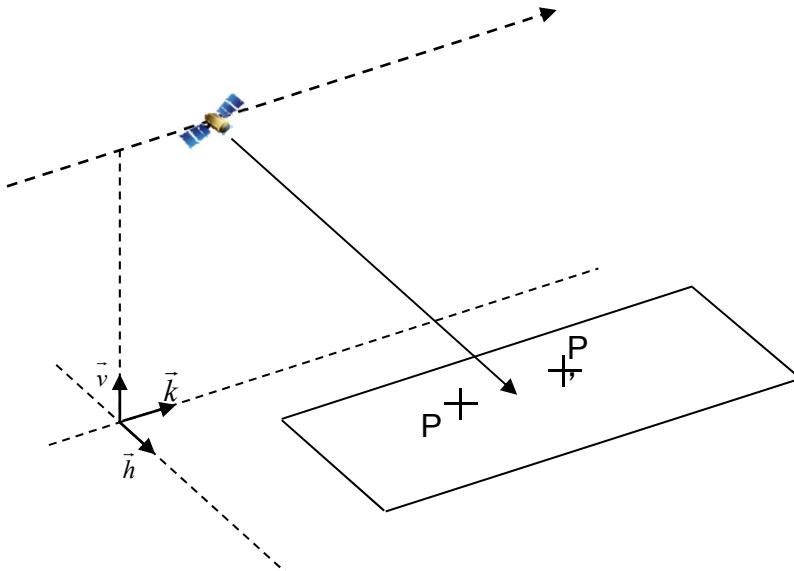
ASAR '11



Bare surfaces hypotheses

- Using bare soil hypotheses:

- Reflection symmetry: $\langle S_{HH} S_{HV}^* \rangle \approx \langle S_{VV} S_{HV}^* \rangle \approx 0$
- Bare soil assumption*: $\text{Arg} \langle S_{HH} S_{VV}^* \rangle \approx 0$ for incidence angles $< 40^\circ$



Reflection symmetry

*A. Guissard, "Phase calibration of polarimetric radars from slightly rough surfaces," IEEE Trans. Geosci. Remote Sens., vol. 32, no. 3, pp. 712–714, May 1994.

Selecting bare surfaces

- Ionosphere interaction

$$M = \begin{pmatrix} M_{RH} \\ M_{RV} \end{pmatrix} = \frac{1}{\sqrt{2}} R_\Omega S R_\Omega \begin{pmatrix} 1 \\ -j \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \cos \Omega & \sin \Omega \\ -\sin \Omega & \cos \Omega \end{pmatrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{pmatrix} \begin{pmatrix} \cos \Omega & \sin \Omega \\ -\sin \Omega & \cos \Omega \end{pmatrix} \begin{pmatrix} 1 \\ -j \end{pmatrix}$$

$$S = \begin{pmatrix} S_{RH} \\ S_{RV} \end{pmatrix} = \frac{1}{\sqrt{2}} S \begin{pmatrix} 1 \\ -j \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{HV} & S_{VV} \end{pmatrix} \begin{pmatrix} 1 \\ -j \end{pmatrix}$$

$$\langle M_{RH} M_{RH}^* \rangle \cong \frac{1}{2} \left(|S_{HH}|^2 \cos^2 \Omega + |S_{HV}|^2 + |S_{VV}|^2 \sin^2 \Omega + j \operatorname{Im}(S_{HH} S_{VV}^*) \cos \Omega \sin \Omega \right)$$

$$\langle M_{RV} M_{RV}^* \rangle \cong \frac{1}{2} \left(|S_{HH}|^2 \sin^2 \Omega + |S_{HV}|^2 + |S_{VV}|^2 \cos^2 \Omega - j \operatorname{Im}(S_{HH} S_{VV}^*) \sin \Omega \cos \Omega \right)$$

$$\boxed{\langle S_{RH} S_{RH}^* \rangle + \langle S_{RV} S_{RV}^* \rangle = \langle M_{RH} M_{RH}^* \rangle + \langle M_{RV} M_{RV}^* \rangle \cong \frac{1}{2} \left(|S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2 \right)}$$

$$\langle M_{RH} M_{RV}^* \rangle \cong \frac{1}{2} \left(|S_{VV}|^2 - |S_{HH}|^2 \right) \cos \Omega \sin \Omega + j S_{HH} S_{VV}^* \cos^2 \Omega - j |S_{HV}|^2 + j S_{VV} S_{HH}^* \sin^2 \Omega$$

$$\operatorname{Re} \langle M_{RH} M_{RV}^* \rangle \cong \frac{1}{2} \left(\left(|S_{VV}|^2 - |S_{HH}|^2 \right) \cos \Omega \sin \Omega - \operatorname{Im}(S_{HH} S_{VV}^*) (\cos^2 \Omega - \sin^2 \Omega) \right)$$

$$\boxed{\operatorname{Im} \langle S_{RH} S_{RV}^* \rangle = \operatorname{Im} \langle M_{RH} M_{RV}^* \rangle \cong \frac{1}{2} \left(\operatorname{Re}(S_{HH} S_{VV}^*) - |S_{HV}|^2 \right)}$$

Selecting bare surfaces - The conformity coefficient

Definition

$$\mu = \frac{2 \operatorname{Im} \langle M_{RH} M_{RV}^* \rangle}{\langle M_{RH} M_{RH}^* \rangle + \langle M_{RV} M_{RV}^* \rangle}$$



ASAR '11



Selecting bare surfaces - The conformity coefficient

$$\mu = \frac{2 \operatorname{Im} \langle M_{RH} M_{RV}^* \rangle}{\langle M_{RH} M_{RH}^* \rangle + \langle M_{RV} M_{RV}^* \rangle} \approx 2 \frac{\operatorname{Re}(S_{HH} S_{VV}^*) - |S_{HV}|^2}{(|S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2)}$$



ASAR '11



Selecting bare surfaces - Four bare surfaces criteria

- Reference criterion:
- Reconstructed ratio HV/VV using JC Souyris* hypotheses:



HV overestimated

- Coherence between M_{RH} and M_{RV} :

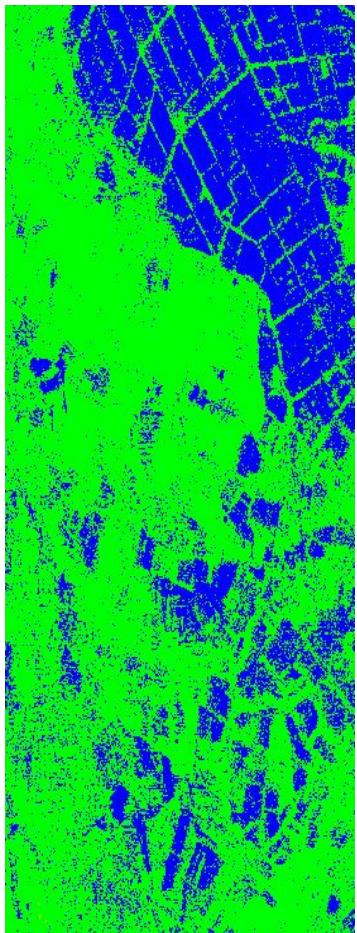
$$\gamma_{M_{RH} M_{RV}^*} = \frac{\langle M_{RH} M_{RV}^* \rangle}{\sqrt{\langle M_{RH} M_{RH}^* \rangle \langle M_{RV} M_{RV}^* \rangle}}$$

- Conformity coefficient:

$$\mu = \frac{2 \operatorname{Im} \langle M_{RH} M_{RV}^* \rangle}{\langle M_{RH} M_{RH}^* \rangle + \langle M_{RV} M_{RV}^* \rangle}$$

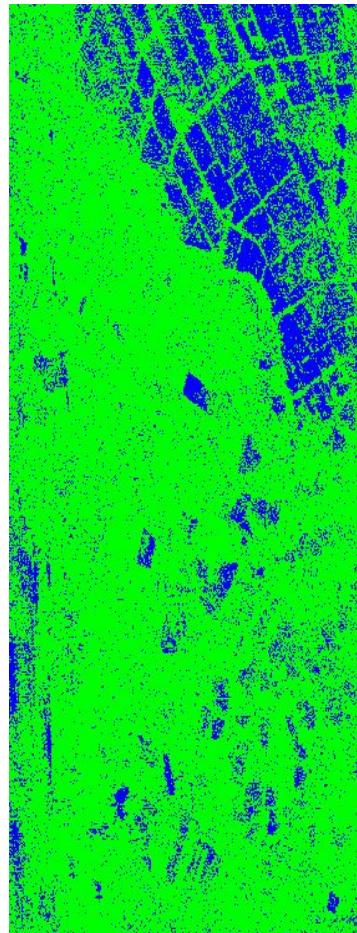
*J-C. Souyris, P. Imbo, R. FjØrtoft, S. Mingot and J-S. Lee, *Compact Polarimetry Based on Symmetry Properties of Geophysical Media : The π/4 Mode*, IEEE Transactions on Geoscience and Remote Sensing, vol. 43, no. 3, March 2005.

Selecting bare surfaces - The indicators



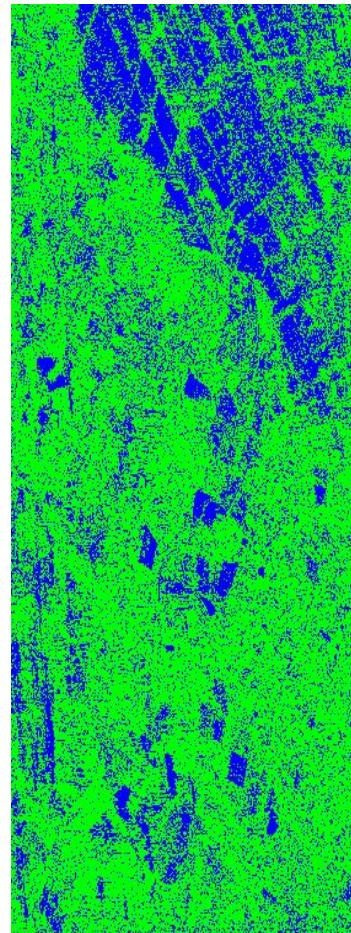
-11dB

$$\frac{\sigma_{HV}^0}{\sigma_{VV}^0}$$



-11dB

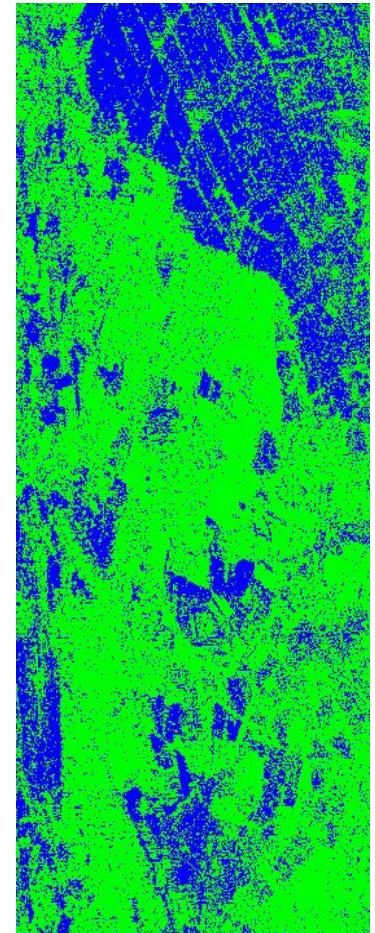
$$\frac{\sigma_{HV}^0}{\sigma_{VV}^0}$$



0 0.61 1

$$\gamma_{M_{RH} M_{RV}^*}$$

ASAR '11



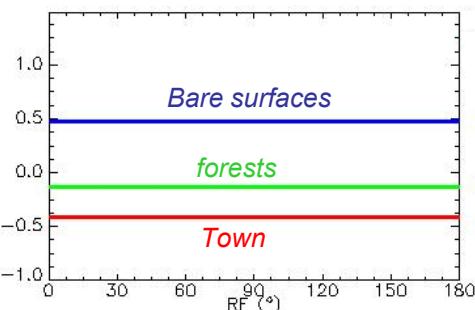
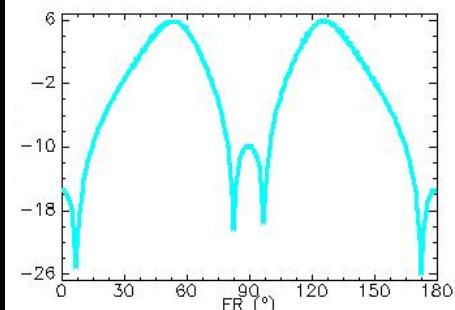
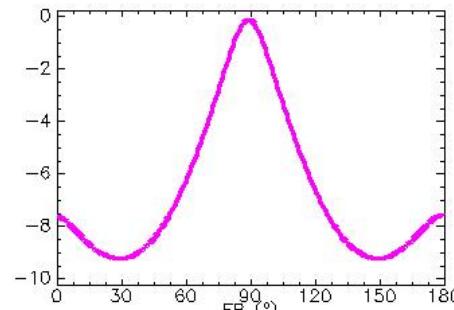
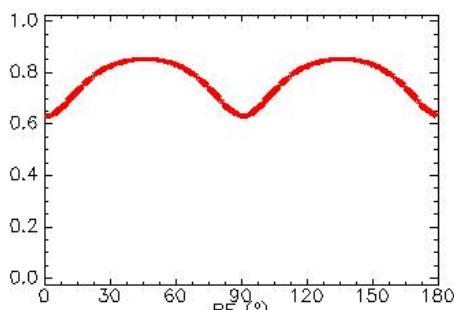
-1 0.3 1

$$\mu$$

JPL

ONERA
THE FRENCH AEROSPACE LAB

Selecting bare surfaces - Comparison of four indicators

	$\frac{\sigma_{HV}^0}{\sigma_{VV}^0}$	$\frac{\sigma_{HV}^0}{\sigma_{VV}^0}$	$\gamma_{M_{RH}M_{RV}^*}$	
μ	$\begin{bmatrix} 20.12\% & 12.70\% \\ 12.68\% & 54.50\% \end{bmatrix}$	$\begin{bmatrix} 14.16\% & 5.54\% \\ 32.86\% & 47.44\% \end{bmatrix}$	$\begin{bmatrix} 23.62\% & 8.54\% \\ 15.67\% & 52.17\% \end{bmatrix}$	
	 <p>Plot showing RF (°) from 0 to 180 on the x-axis and value on the y-axis. Three horizontal lines represent different surface types: 'Bare surfaces' (blue, ~0.5), 'forests' (green, ~0), and 'Town' (red, ~-0.5).</p>	 <p>Plot showing RF (°) from 0 to 180 on the x-axis and value on the y-axis. A cyan curve shows two peaks at approximately 60° and 120°, with deep troughs around 90°.</p>	 <p>Plot showing RF (°) from 0 to 180 on the x-axis and value on the y-axis. A magenta curve shows a single sharp peak at 90°.</p>	 <p>Plot showing RF (°) from 0 to 180 on the x-axis and value on the y-axis. A red curve shows a smooth, periodic oscillation between 0.6 and 0.8.</p>

Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - ...
- Classification
- Summary



ASAR '11



Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
- Summary

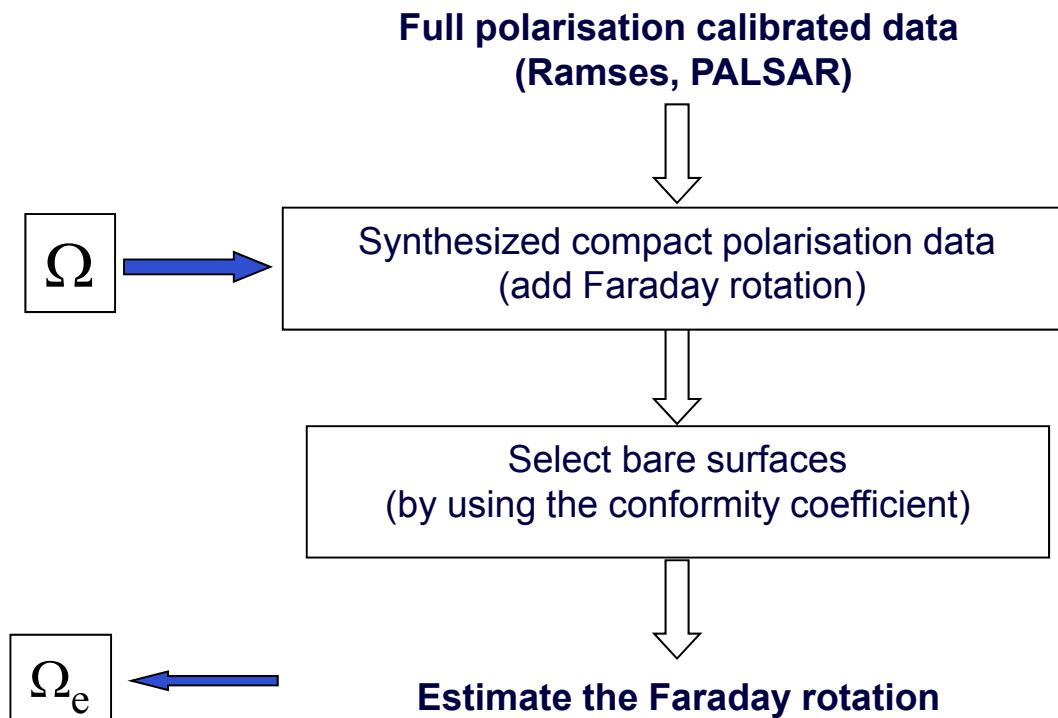


ASAR '11



Process

- Flow diagram of the process



Faraday rotation estimate

- Using full polarisation data

- Freeman method (2004,FP data) $\Omega = \pm \frac{1}{2} \tan^{-1} \sqrt{\frac{4 \langle Z_{HV} Z_{HV}^* \rangle}{\langle M_{HH} M_{HH}^* \rangle + \langle M_{VV} M_{VV}^* \rangle + 2 \operatorname{Re} \langle M_{HH} M_{VV}^* \rangle}} \pm \frac{\pi}{4}$
with $Z_{hv}=0.5(M_{vh}-M_{hv})$

- Bickel and Bates (FP linear data transformed in circular basis)

$$\Omega = \frac{1}{4} \arg \langle M_{RL} M_{LR}^* \rangle \pm \frac{\pi}{4}$$



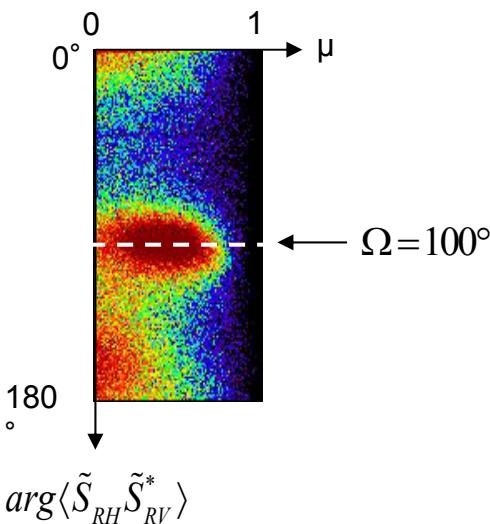
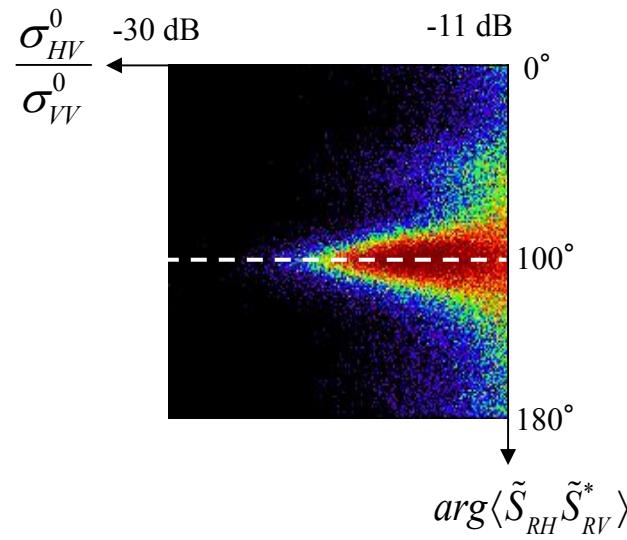
ASAR '11



Faraday rotation estimate over RAMSES P-band data

$$\Omega=100^\circ$$

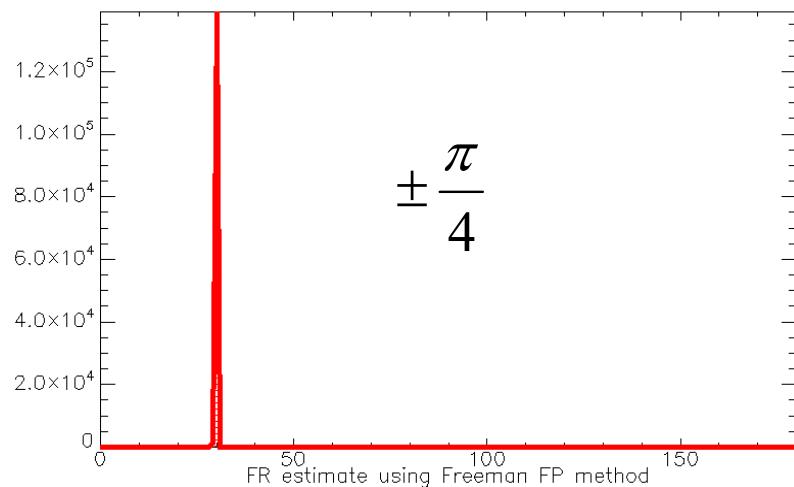
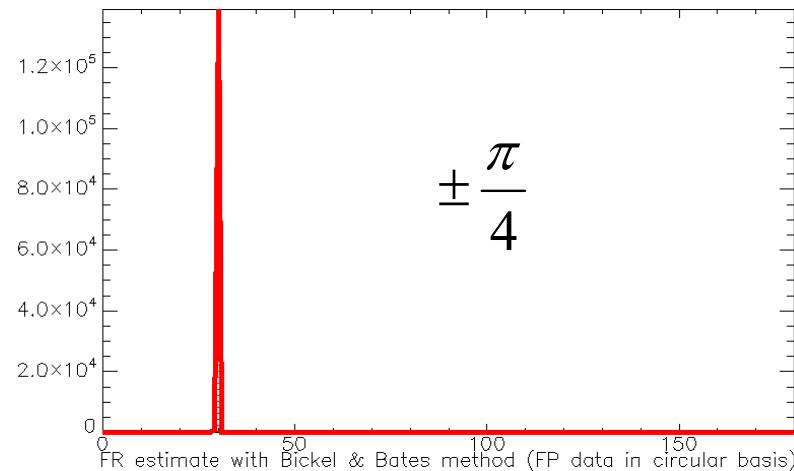
$$\arg\left\langle \tilde{S}_{RH}\tilde{S}_{RV}^* \right\rangle = 90^\circ \pm 180^\circ$$



Faraday rotation estimate over PALSAR L-band data

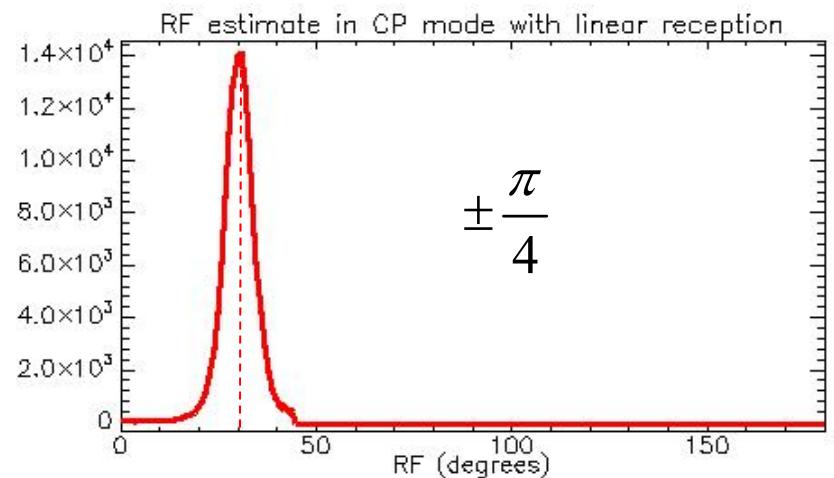
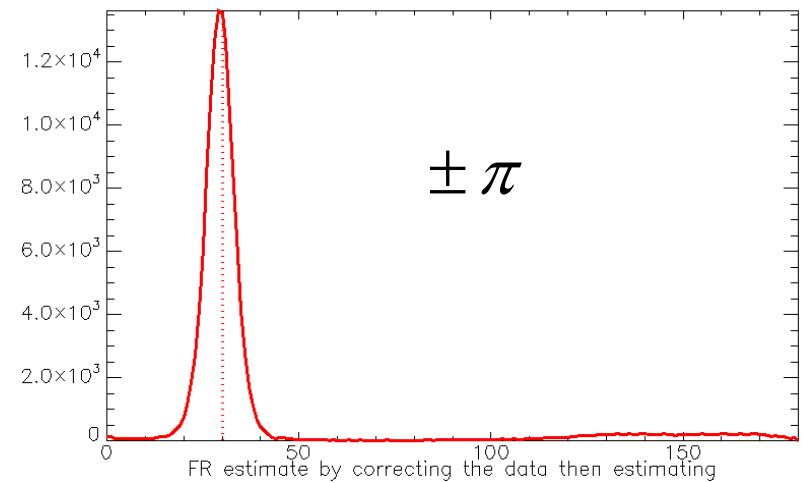
Full polarimetric data

$$\Omega=30^\circ$$



Compact polarimetric data

Over bare surfaces $\mu > 0.3$



Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
- Summary



ASAR '11



Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
- Summary



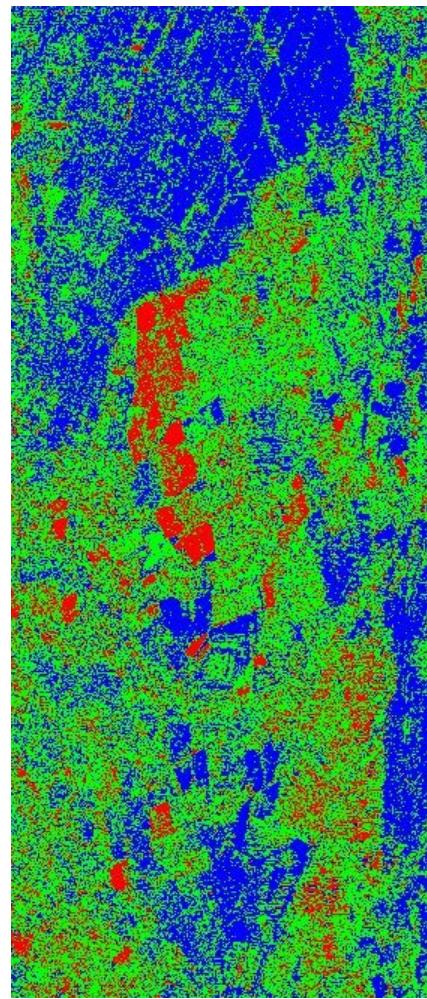
ASAR '11



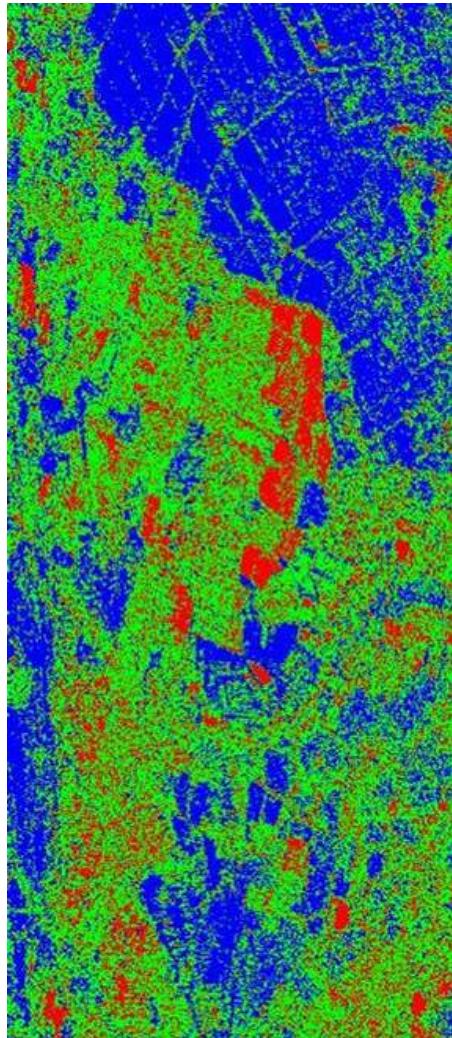
The conformity coefficient – μ classifier

$$\mu = \frac{2 \operatorname{Im} \langle M_{RH} M_{RV}^* \rangle}{\langle M_{RH} M_{RH}^* \rangle + \langle M_{RV} M_{RV}^* \rangle} \approx 2 \frac{\operatorname{Re}(S_{HH} S_{VV}^*) - |S_{HV}|^2}{(|S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2)}$$

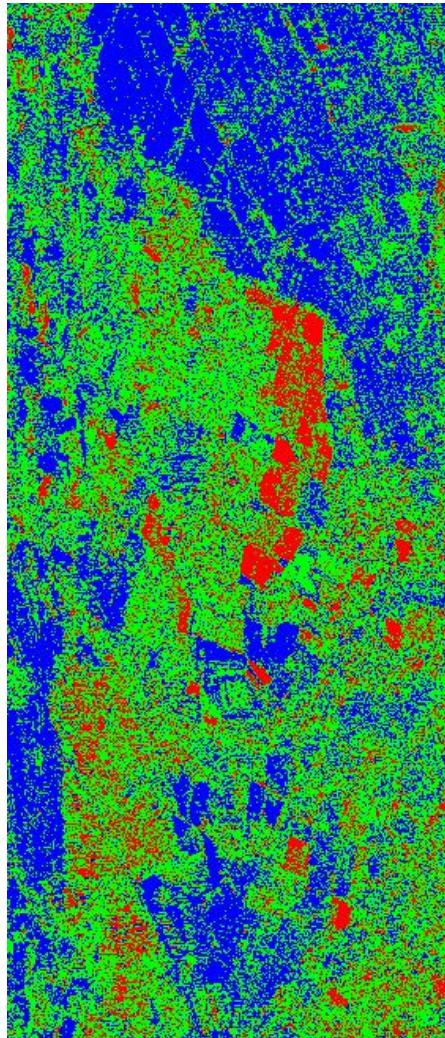
μ classifier - RAMSES, P-band, St Germain d' Esteuil



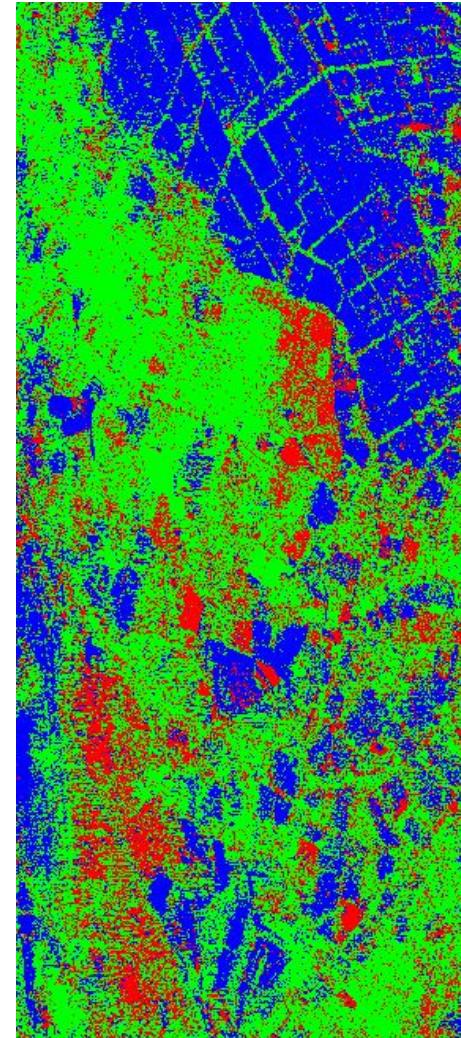
Qualitative analysis of μ -classification



Claude-Pottier classification



Conformity coefficient



Freeman-Durden classification

Double-bounce

Volume

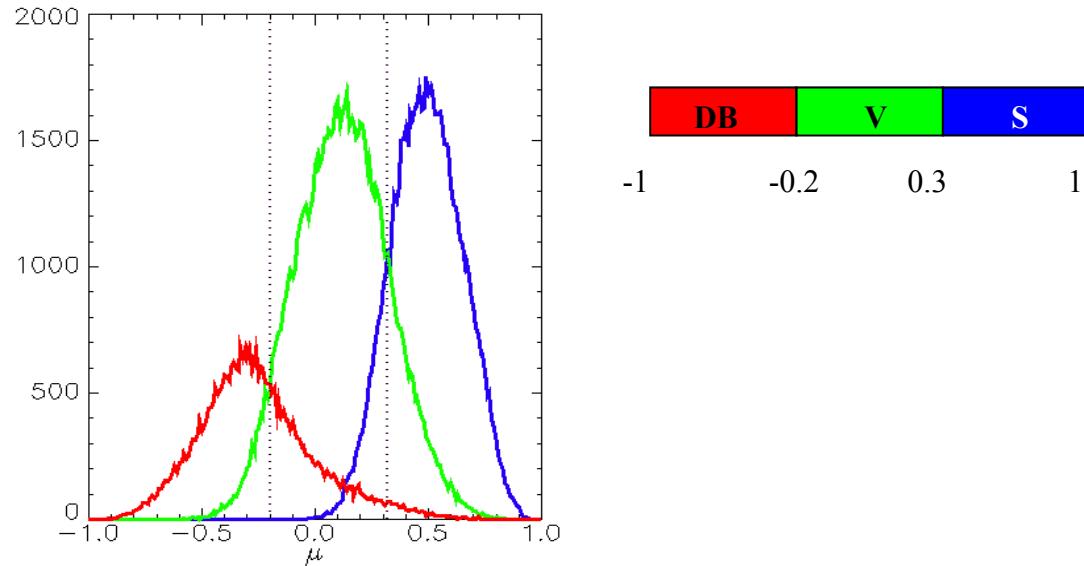
Surface

$Pv > 0.6 Pd$ and $Pv > 0.3 Ps$

$Ps > Pd$
 Pd

Quantitative analysis of μ -classification

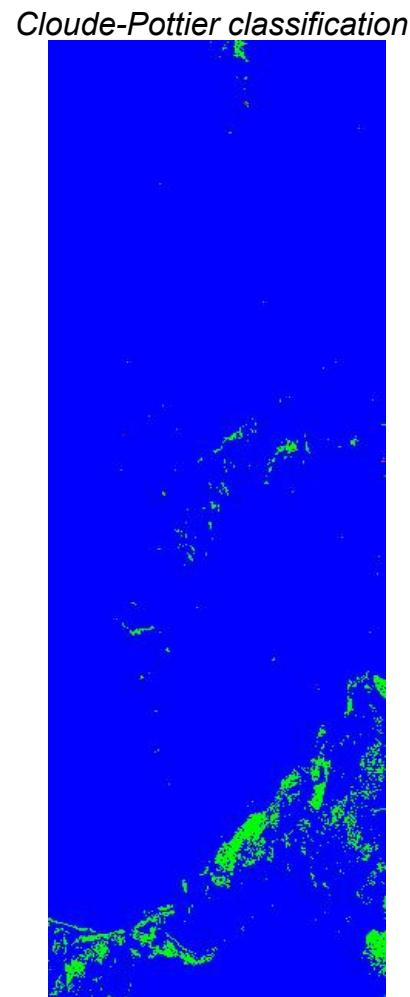
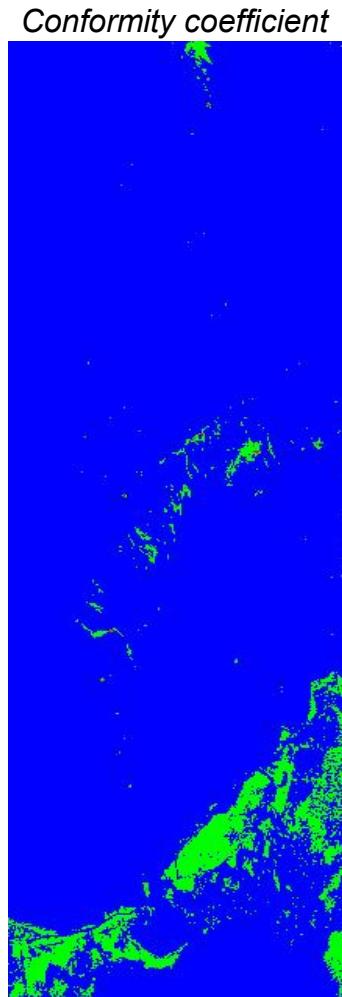
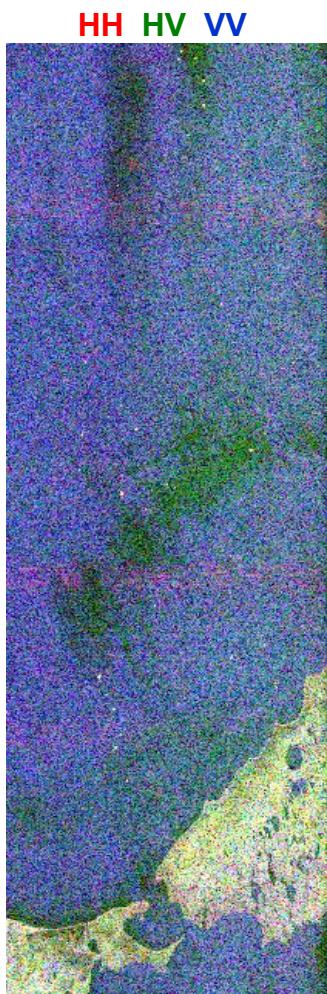
- Conformity coefficient versus Claude-Pottier



- Confusion matrices

H / α			FD		
	S	V	DB		S
μ	S	30.31	6.23	0.44	S
	V	6.66	36.26	2.06	V
	DB	0.04	6.54	11.46	DB

μ classifier over PALSAR L-band data



H / α

	S	V	DB
S	94.23	0.01	0.00
μ	3.12	2.61	0.00
DB	0.00	0.02	0.01

Double-bounce Volume Surface

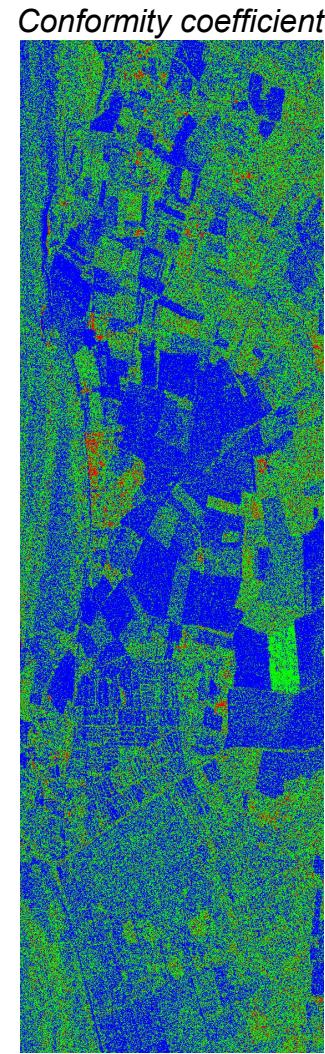
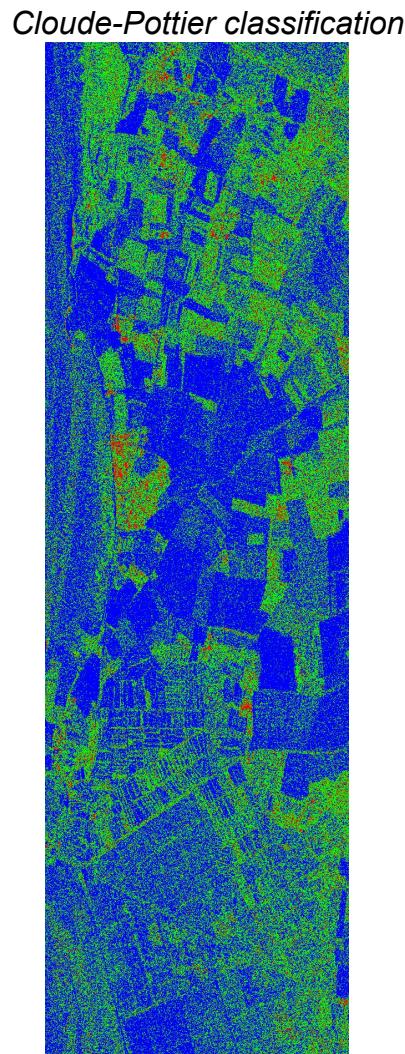
JPL

ASAR '11

IETR
INSTITUT D'ÉLECTRONIQUE ET DE TÉLÉCOMMUNICATIONS DE REIMS

ONERA
THE FRENCH AEROSPACE LAB

μ classifier over RAMSES L-band data, Le Moulin du Fâ



H / α

	S	V	DB
S	43.2	2.62	0.08
μ	12.89	32.2	1.67
DB	0.00	2.31	4.96

Double-bounce

Volume

Surface

JPL

ASAR '11

IETR
INSTITUT D'ÉLECTRONIQUE ET DE TÉLÉCOMMUNICATIONS DE RENNES

ONERA
THE FRENCH AEROSPACE LAB

Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
 - Classification using the conformity coefficient
 - ...
- Summary



ASAR '11



Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
 - Classification using the conformity coefficient
 - Classification of different types of vegetation
- Summary

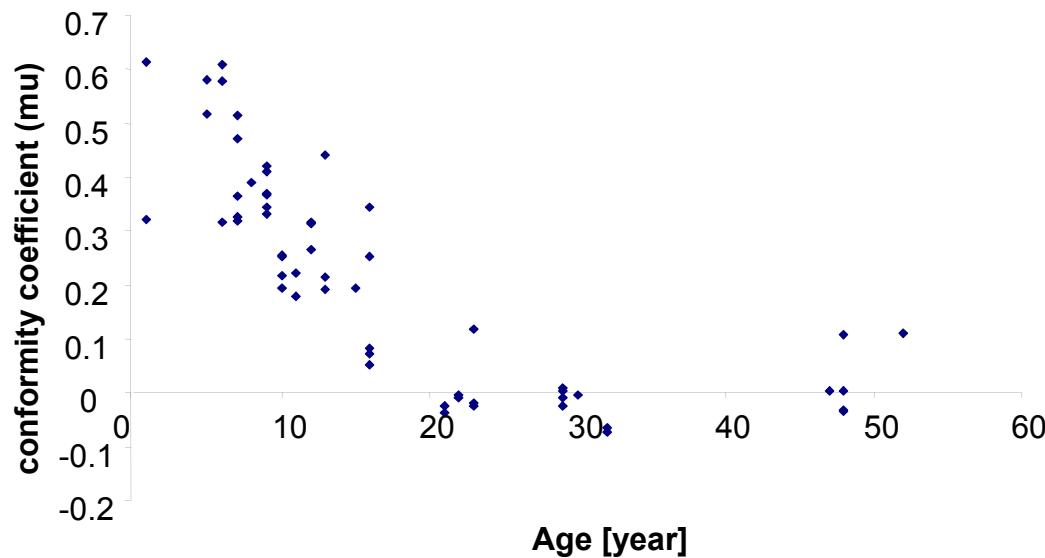


ASAR '11



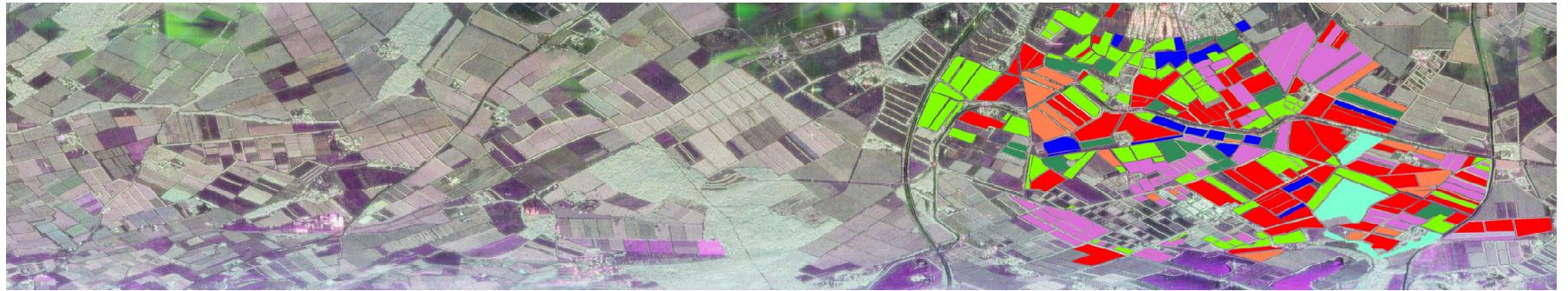
Behavior of μ with forest ages

RAMSES data, Nezer, 2001, P-band

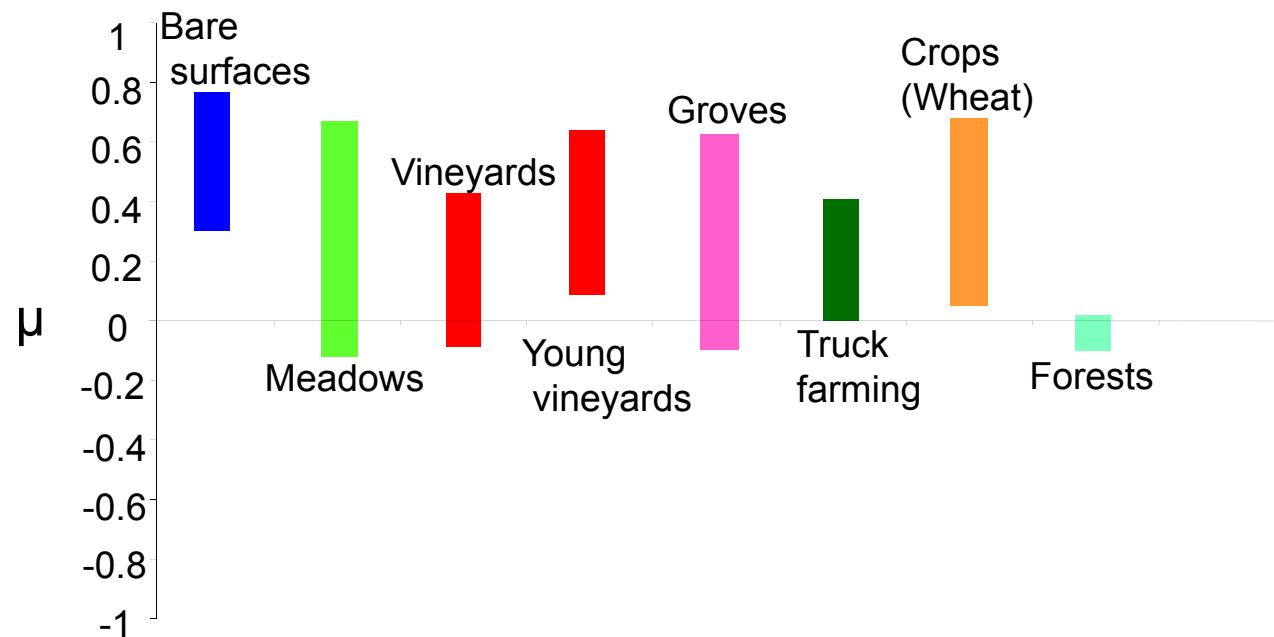


- Young forest plots act as bare surfaces
 - $0.2 < \mu < 1$
- Old forest plots act as volume
 - $\mu \sim 0$

μ over different types of vegetation



SETHI FP data, L-band, Garons



Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
 - Classification using the conformity coefficient
 - Classification of different types of vegetation
- Summary



ASAR '11



Overview

- Background
- Calibration
 - Description and suggested approach
- Faraday rotation
 - Some basic properties
 - Bare surfaces requirement → conformity coefficient
 - Faraday rotation estimate
- Classification
 - Classification using the conformity coefficient
 - Classification of different types of vegetation
- Summary



ASAR '11



Summary: systems implications

- Compact-pol allows
 - To acquire larger swath (versus FP)
 - To access wider incidence angle range (versus FP)
 - To avoid Faraday rotation in transmission (versus DP)
- Calibration
 - A solution with 3 external targets
- Estimation of Faraday rotation possible
 - Over bare surfaces selected by the conformity coefficient which
 - Is FR independent
 - Can be used with CP data as well as FP data
 - Allows distinguishing 3 different types of scattering
 - Using 3 methods with circular transmission and two circular OR linear receptions
 - One modulo $\pi/4$
 - Two modulo π